Spin Asymmetries for High-$\mathrm{p_T}$ Pions and Jets

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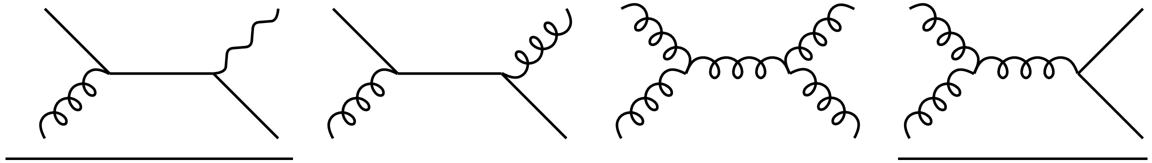
- *brief tour: QCD framework*
- *results: pions and jets at mid and forward rapidities*
- *outlook: calculations in the pipeline*

Cross sections relevant for RHIC spin

main goal of RHIC spin program with longitudinal polarization:

pin down all aspects of helicity pdfs, in particular the poorly known Δg

$\longrightarrow$ study processes with a *dominant* gluon contribution in LO:



reaction	LO subprocesses	partons probed	x-range ($\eta = 0$)
$pp \to$ jets X	$q\bar{q}, qq, qg, gg \to$ jet X	Δq, Δg	$x \gtrsim 0.03$
$pp \to \pi X$	$q\bar{q}, qq, qg, gg \to \pi X$	Δq, Δg	$x \gtrsim 0.03$
$pp \to \gamma X$	$qg \to q\gamma$, $q\bar{q} \to g\gamma$	Δg	$x \gtrsim 0.03$
$pp \to Q\bar{Q}X$	$gg \to Q\bar{Q}$, $q\bar{q} \to Q\bar{Q}$	Δg	$x \gtrsim 0.01$
$pp \to W^{\pm}X$	$q\bar{q}' \to W^{\pm}$	Δu, $\Delta\bar{u}$, Δd, $\Delta\bar{d}$	$x \gtrsim 0.06$

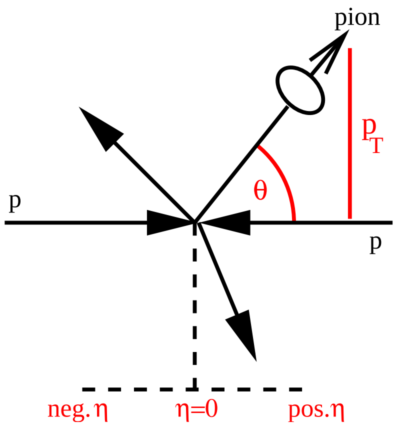
Perturbative QCD approach for hadron-hadron cross sections

starting point: • exploit universality of pdf's

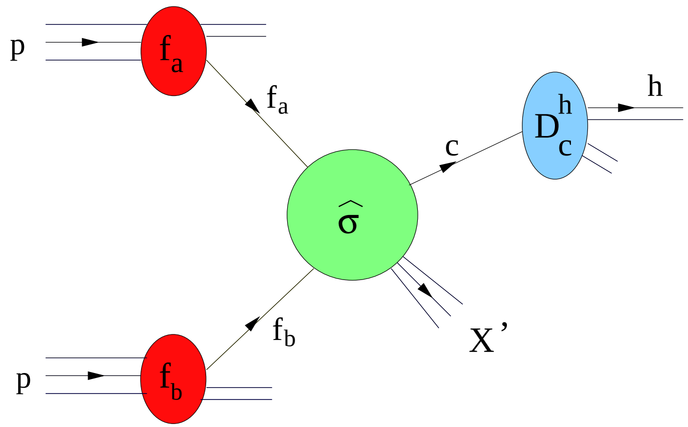
• invoke *factorization* Libby, Sterman; Ellis et al.; Amati et al.; Collins et al.; . . .

$\longrightarrow$ way to separate long-distance (= non-perturbative) from short-distance (= perturbative) phenomena

example: (un)polarized high-p_T single-inclusive hadron production



factorization $\longrightarrow$ theorem



ingredients: parton densities $f_a(x_a)$, $f_b(x_b)$, fragmentation fcts. $D_c^h(z)$,

hard partonic cross section $\hat{\sigma}$

Factorized $\vec{p}\vec{p}$ cross sections

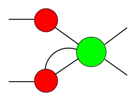
long-distance

from exp.; μ-dep.: $d\sigma/d\mu = 0$ (pQCD)

$$\frac{d\Delta\sigma^{\vec{p}\vec{p}\to\pi X}}{dp_T d\eta} = \sum_{abc}\int dx_a\,dx_b\,dz_c\,\Delta f_a(x_a,\mu_f)\,\Delta f_b(x_b,\mu_f)\,D_c^\pi(z_c,\mu_f')$$
$$\times\ \frac{d\Delta\hat{\sigma}^{ab\to cX'}}{dp_T d\eta}(x_a P_a, x_b P_b, P^\pi/z_c, \mu_f, \mu_f', \mu_r) + \mathcal{O}(\frac{\lambda}{p_T})^n$$

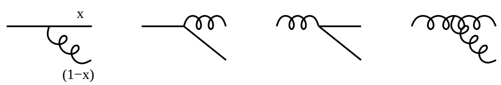
short-distance

calculable in pQCD: power series in α_s

power corrections 

neglected

- separation of long- ($\Delta f_{a,b}$, D_c^h) and short-distance ($d\Delta\hat{\sigma}$) physics not unique
  - controlled by arbitrary *factorization scales* μ_f and $\mu_f' \simeq \mathcal{O}(p_T)$

    [amount of "parton radiation" 

    included in $\Delta f_{a,b}$, D_c^h]
  - another arbitrary scale controls the running of α_s: *renormalization scale* μ_r

Factorized $\vec{p}\vec{p}$ cross sections (cont.)

measured cross section *must not* depend on theoretical scales: $\mu_f \frac{d\Delta\sigma}{d\mu_f} = 0$

$\leftrightarrow d\Delta\hat{\sigma}(\mu_f \to \mu_f + d\mu_f, \mu'_f)$ canceled by scale behavior of $\Delta f_{a,b}(x_{a,b}, \mu_f)$

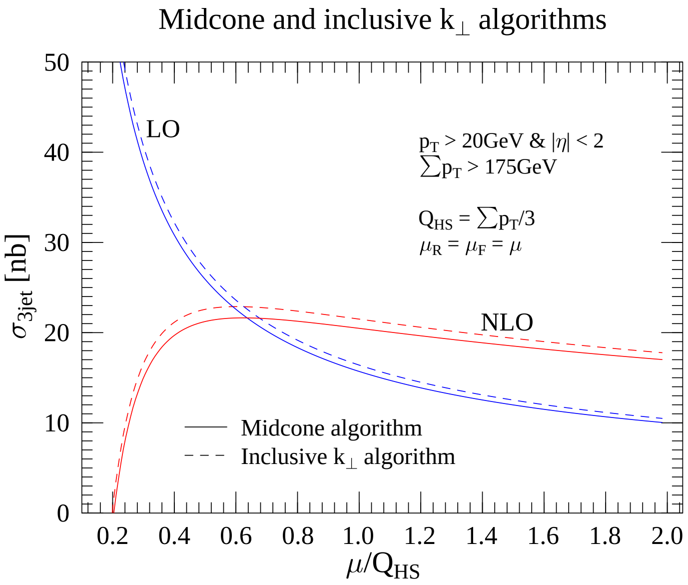
catch: . . . we work with a perturbative expansion in α_s:

$$d\Delta\hat{\sigma} = \overset{\text{LO}}{d\Delta\hat{\sigma}^{(0)}} + \overset{\text{NLO}}{\alpha_s\, d\Delta\hat{\sigma}^{(1)}} + \overset{\text{NNLO}}{\alpha_s^2\, d\Delta\hat{\sigma}^{(2)}} + \ldots$$

μ_f cancellation only happens to all orders

LO	:	no cancellation whatsoever
NLO	:	cancellation starts to work
NNLO	:	better and better
. . .		

$\longrightarrow$ higher order calculations mandatory



typical example: 3-jets @ TeVatron (Z. Nagy)

NLO corrections in a nutshell

going beyond the LO is in every respect a major enterprise . . .

$$d\Delta\hat{\sigma} = \overset{\text{LO}}{d\Delta\hat{\sigma}^{(0)}} + \overset{\text{NLO}}{\alpha_s\, d\Delta\hat{\sigma}^{(1)}} + \overset{\text{NNLO}}{\alpha_s^2\, d\Delta\hat{\sigma}^{(2)}} + \ldots$$

number of partons

complexity of calculation

- NLO techniques are well established and most cross sections are available
- NNLO still far from being standard, a lot of progress though

recent example: the NNLO DGLAP evolution kernels P_{ij} Moch, Vermaseren, Vogt

$\longrightarrow$ NNLO = pushing computer algebra programs to their limits

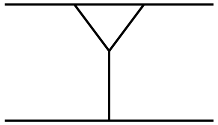
	# diagrams	# integrals
LO	18	a few
NLO	350	some more
NNLO	9607	$\sim 10^5$

NLO corrections in a nutshell (cont.)

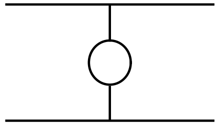
at $\mathcal{O}(\alpha_s^3)$ (NLO) one has to consider:

- one-loop (virtual) corrections to all LO $2 \to 2$  processes

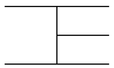
"box"



"vertex"



"selfenergy"

- all conceivable $2 \to 3$  parton-parton scattering processes

  this includes additional gluon emission to existing LO processes

$$qq' \to qq'g,\ q\bar{q} \to ggg,\ gg \to ggg, \text{ etc.}$$

  as well as genuine NLO processes not possible at $\mathcal{O}(\alpha_s^2)$

$$qg \to qq'\bar{q}',\ qg \to qq\bar{q}, \text{ etc.}$$

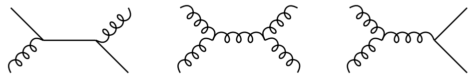
NLO corrections in a nutshell (cont.)

good news: steady progress – list of results relevant for RHIC spin:

evol. kernels	ΔP_{ij}	NLO	Mertig, van Neerven; Vogelsang
hadrons	$\vec{p}\vec{p} \to H + X$	NLO	De Florian; Jäger, Schäfer, MS, Vogelsang
	$\vec{p}\vec{p} \to H_1 + H_2 + X$	NLO	Jäger, Owens, MS, Vogelsang (very soon)
	$p\vec{p} \to \vec{H} + X$	NLO	Jäger, MS, Vogelsang (in preparation)
jets	$\vec{p}\vec{p} \to \mathrm{jet(s)} + X$	NLO	De Florian et al.; Jäger, MS, Vogelsang
prompt γ	$\vec{p}\vec{p} \to \gamma + X$	NLO	Gordon, Vogelsang; Contogouris et al.
	$\vec{p}\vec{p} \to \gamma\gamma + X$	NLO	Coriano, Gordon
	$p\vec{p} \to \vec{\gamma} + X$	NLO	Vogelsang
γ + jet	$\vec{p}\vec{p} \to \gamma + \mathrm{jet} + X$	NLO	Gordon
γ + charm	$\vec{p}\vec{p} \to \gamma + c + X$	NLO	Berger et al. ($m_c = 0$)
heavy quarks	$\vec{p}\vec{p} \to Q\bar{Q}X$	NLO	Bojak, MS
Drell-Yan	$\vec{p}\vec{p} \to (\gamma^*)X$	NLO	Weber; Gehrmann;
		NNLO	Smith et al.
vector bosons	$\vec{p}\vec{p} \to (Z^0, W^\pm)X$	NLO	Weber; Gehrmann
	$p\vec{p} \to (Z^0, W^\pm)X$	NLO	Weber; Gehrmann

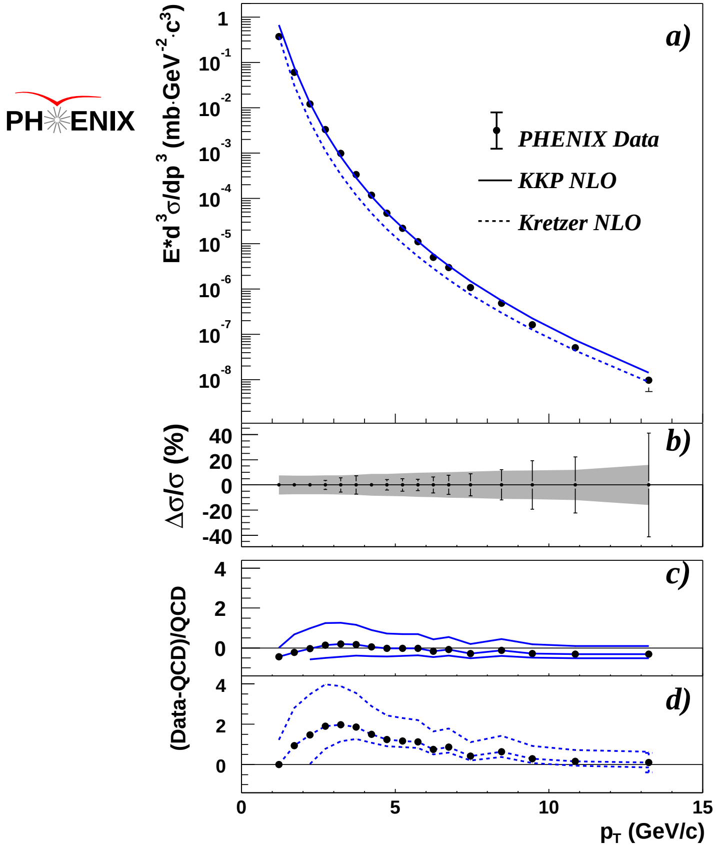
High-p_T Hadron Production at RHIC

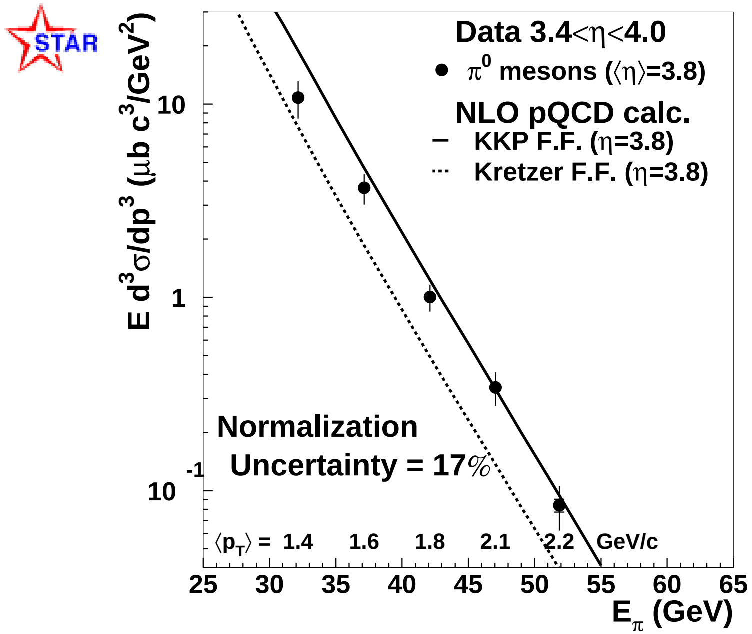
high-p_T pions:



NLO: Jäger, MS, Vogelsang; de Florian

recall: 1^{st} *unpolarized* measurements at RHIC agree well with pQCD



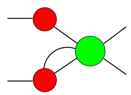


- $D^\pi(z)$ set of KKP favored by data

$\longrightarrow$ foundation for similar measurements with polarization

Interlude: importance of unpolarized cross sections

unpolarized measurements should always precede an A_{LL} measurement:

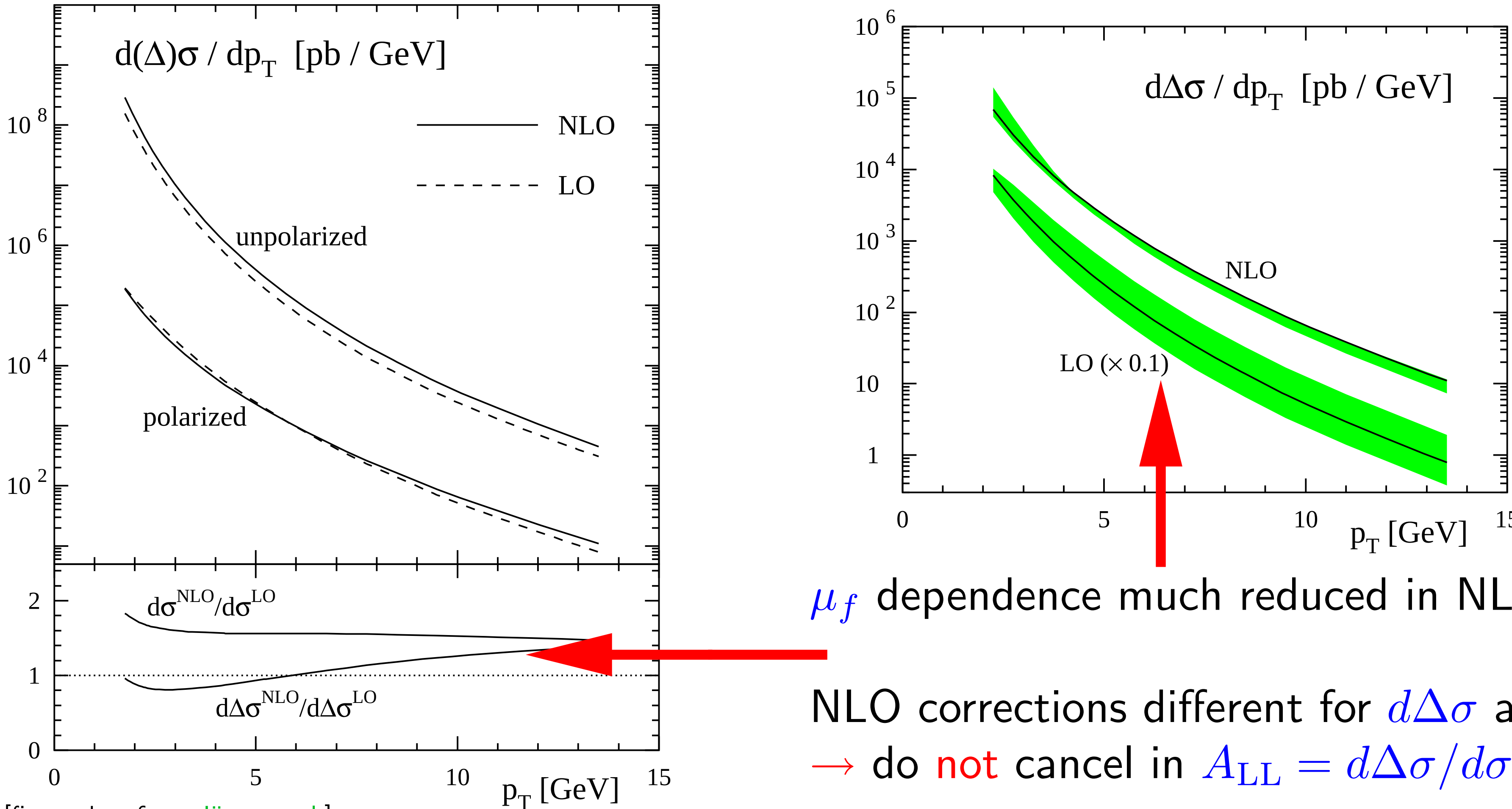
- demonstrate applicability of standard perturbative QCD methods
  - not a priori known where power corrections  , etc. set in
- measurements at $\sqrt{S} = 200\,\mathrm{GeV}$ never done before
  - allows us to study energy dependence of cross sections at a given p_T

    (fixed target) $\rightarrow$ RHIC $\rightarrow$ SPS $\rightarrow$ Tevatron $\rightarrow$ LHC
- valuable source of information about non-perturbative functions
  - e.g. to improve our understanding of hadronization (fragmentation functions)

    $\longrightarrow$ reduces theoretical uncertainties of subsequent extractions of, e.g., Δg!

High-p_T Hadron Production at RHIC (cont.)

a closer look at pQCD results for π^0-production at $\sqrt{S} = 200\,\mathrm{GeV}$, $|\eta| \leq 0.38$:



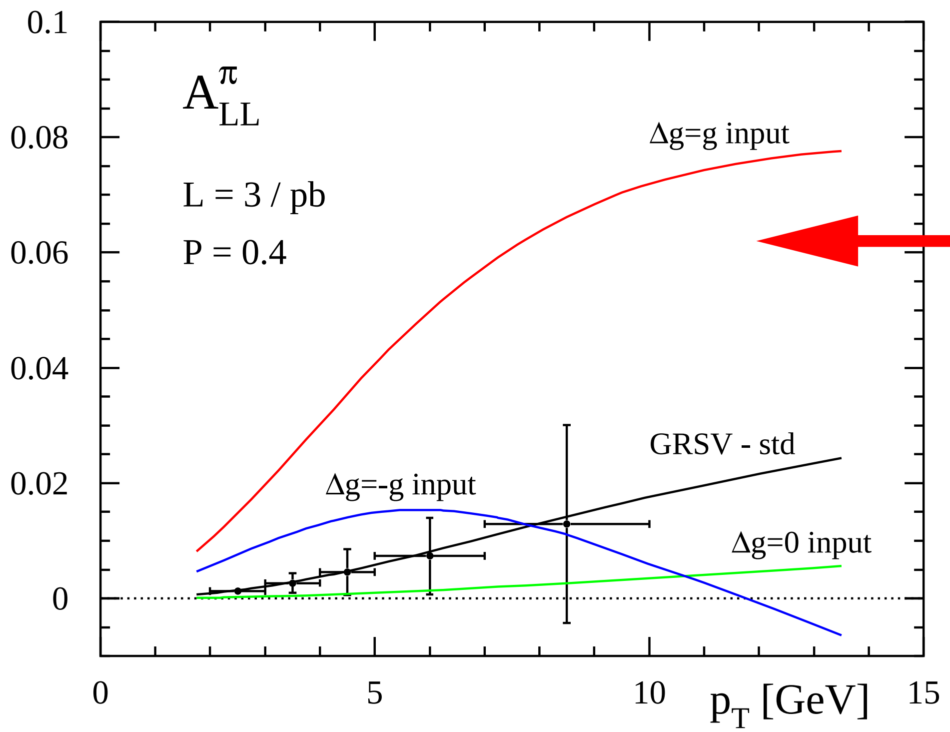
[figs. taken from Jäger et al.]

μ_f dependence much reduced in NLO

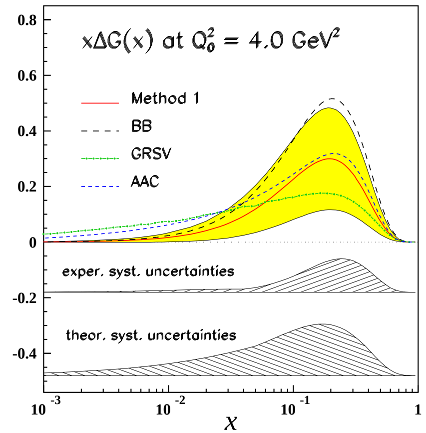
NLO corrections different for $d\Delta\sigma$ and $d\sigma$
$\rightarrow$ do not cancel in $A_{\mathrm{LL}} = d\Delta\sigma/d\sigma$

High-p_T Hadron Production at RHIC (cont.)

Is the spin asymmetry A_{LL} sensitive to unknown gluon polarization Δg ?



predictions for very different Δg



all compatible with current DIS data

estimate of statistical precision:

$$\delta A_{LL} \simeq \frac{1}{\mathcal{P}^2} \frac{1}{(\mathcal{L} d\sigma_{\text{bin}})^{1/2}}$$

$\mathcal{P}$: beam polarization; $\mathcal{L}$: integrated luminosity

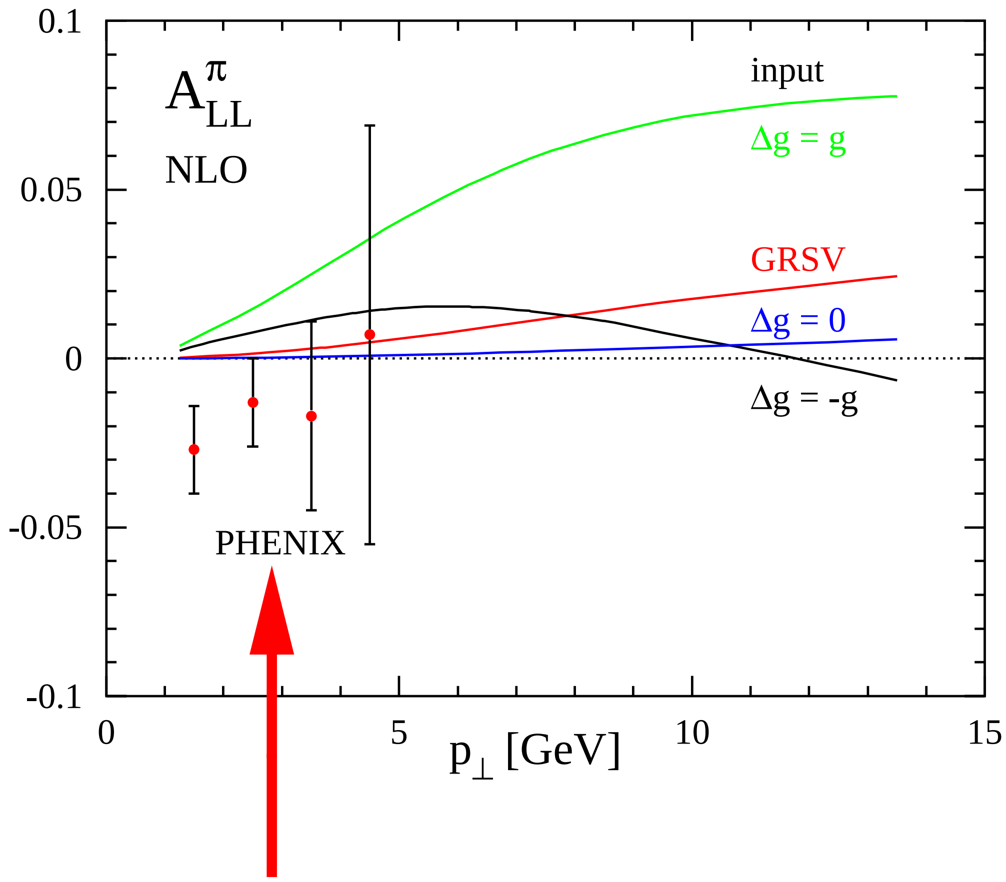
note:

(1) for $p_T \leq 10\,\text{GeV}$: $A_{LL} > 0$

(2) $\mathcal{L} = 3\,\text{pb}^{-1}$ assumed

High-p_T Hadron Production at RHIC (cont.)

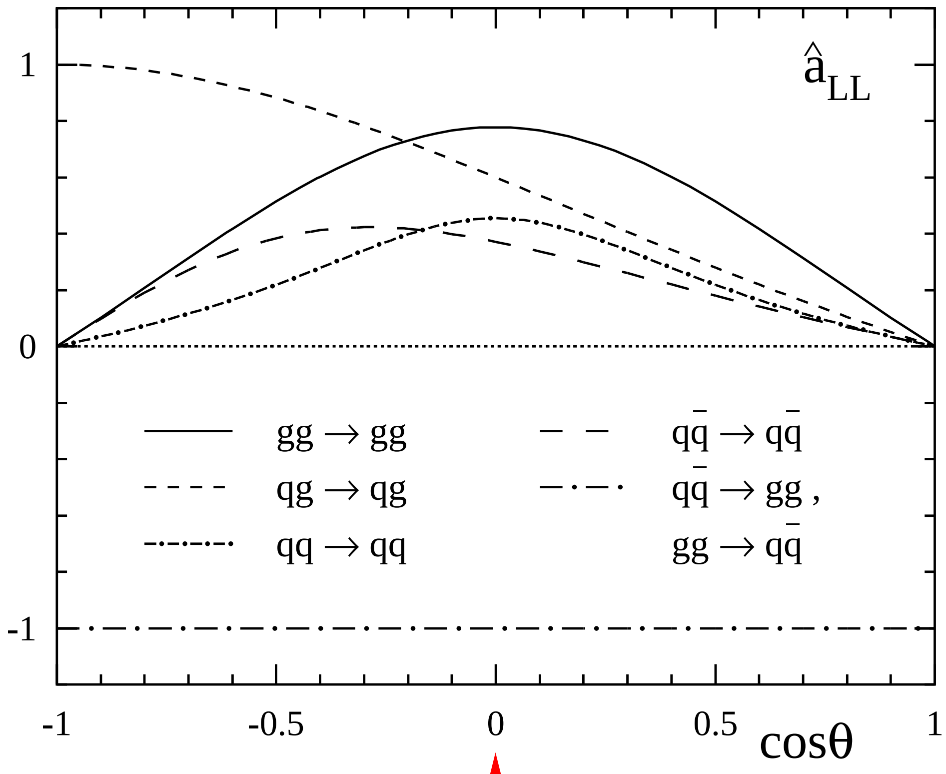
discussion of first results on A_{LL}:



trend for $A_{\mathrm{LL}} < 0$ at small p_T contrary to expectations

High-p_T Hadron Production at RHIC (cont.)

How can *that* be?



PHENIX measures at central rapidities

Naive analysis:

need process with $\hat{a}_{\rm LL} < 0$

recall partonic asymmetries

$$gg \to gg \quad \hat{a}_{\rm LL} > 0$$

$$gg \to q\bar{q} \quad \hat{a}_{\rm LL} = -1$$

$$gq \to gq \quad \hat{a}_{\rm LL} > 0$$

conclude:

$gg \to q\bar{q}$ resp. for neg. $A_{\rm LL}^{\pi}$

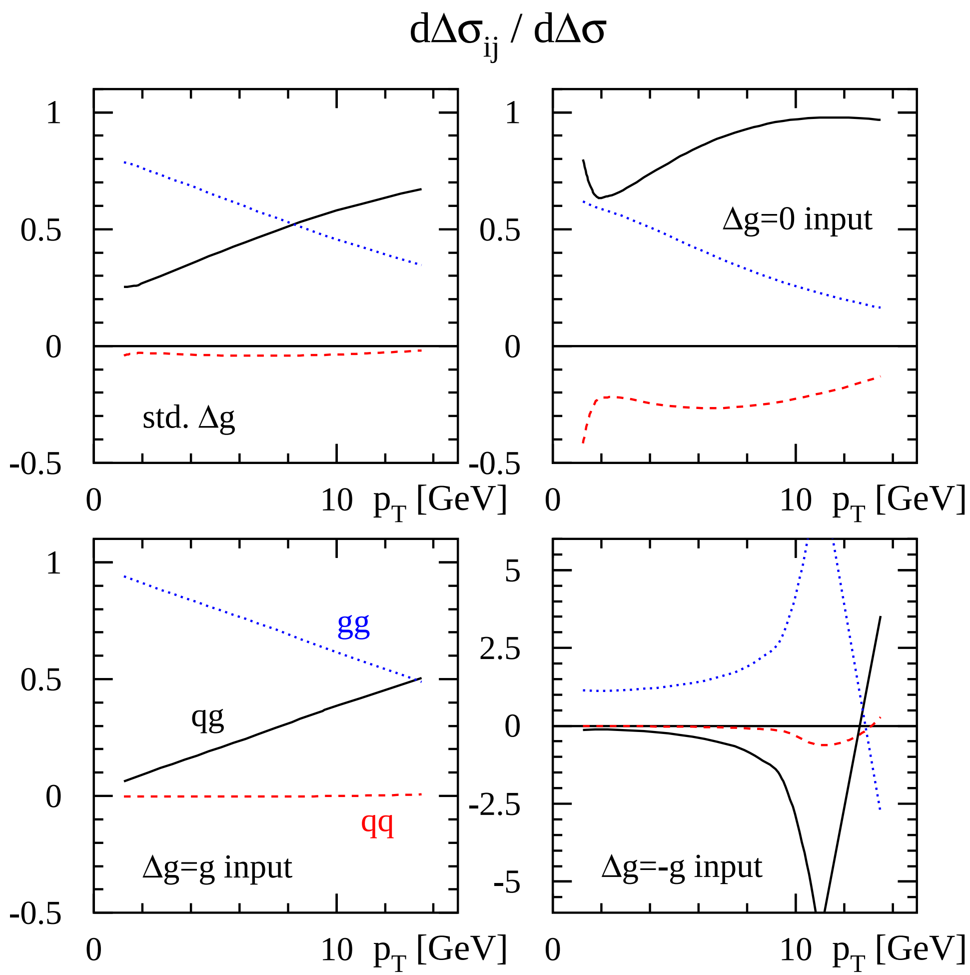
NO!

$$\Delta\hat{\sigma}_{gg\to gg} \underset{(\eta\simeq 0)}{\simeq} 160\,\Delta\hat{\sigma}_{gg\to q\bar{q}}$$

High-p_T Hadron Production at RHIC (cont.)

So - can A_{LL}^{π} be negative?

Jäger, Kretzer, MS, Vogelsang



subprocess contributions:

fairly independent on what one assumes about Δg:

gg processes:
dominate for $p_T \lesssim 10\,\mathrm{GeV}$

qg processes:
take over for $p_T \gtrsim 10\,\mathrm{GeV}$

qq processes:
always small unless p_T very large

High-$\mathbf{p_T}$ Hadron Production at RHIC (cont.)

not yet taken into account:

both partons are not probed at the same momentum fraction x

$\longrightarrow$ even for $\hat{a}_{\rm LL} > 0$ we can have $A_{\rm LL} < 0$ *if* $\Delta f_a(x_a)\Delta f_b(x_b) < 0$

we can even *analytically* derive a lower bound on $A_{\rm LL}$:

$$\frac{d\Delta\sigma}{dp_T} = \sum_{a,b,c} \Delta f_a(x_a) \otimes \Delta f_b(x_b) \otimes \frac{d\Delta\hat{\sigma}_{ab}(x_a, x_b, z_c)}{dp_T} \otimes D_c^h(z_c)$$

take $x_T^2 \equiv 4p_T^2/S$ moments $\int dx_T^2 (x_T^2)^{N-1} \ldots \longrightarrow$ convolutions turn into products

$$\Delta\sigma^\pi(N) = \left(\Delta g^{N+1}\right)^2 \underset{gg}{\underset{\updownarrow}{\mathcal{A}^N}} + 2\Delta g^{N+1} \underset{qg}{\underset{\updownarrow}{\mathcal{B}^N}} + \underset{qq}{\underset{\updownarrow}{\mathcal{C}^N}}$$

this is a parabola in $\Delta g^N \longrightarrow$ minimize!

High-$\mathbf{p_T}$ Hadron Production at RHIC (cont.)

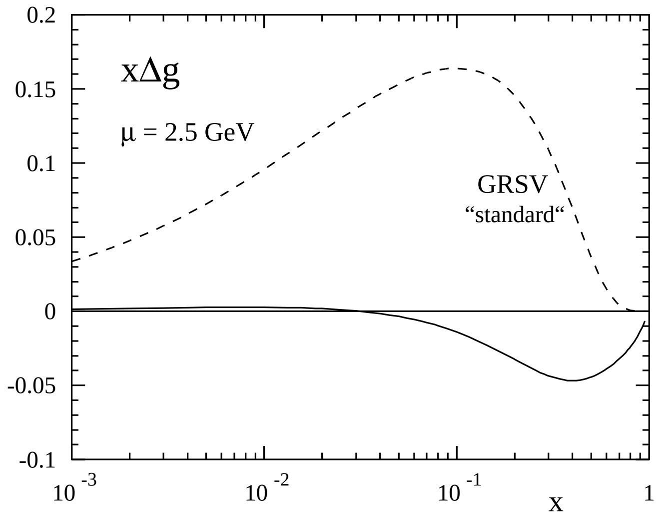
minimization yields: $\Delta\sigma^{\pi}(N)\Big|_{\min} = -\frac{\left(\mathcal{B}^N\right)^2}{\mathcal{A}^N} + \mathcal{C}^N$

$\rightarrow$ negative, but tiny *lower bound* $A_{\rm LL}^{\pi}\big|_{\min} \simeq \mathcal{O}(-10^{-3}) \ggg$ indications from data

as expected:

the resulting Δg has a node

i.e., $\Delta g(x_a)\Delta g(x_b) < 0$



but still way too early to cry!

- “problem” only in lowest p_T bin where uncertainties are large
- p_T perhaps too small to apply pQCD [it works for $d\sigma/dp_T$ though!]

we need much more data to call this a new “spin surprise”

High-p_T Hadron Production at RHIC (cont.)

another lesson: around mid-rapidity and for $p_T \lesssim 10\,\mathrm{GeV}$ it is difficult to even pin down the sign of Δg

reason: gg dominance and $\eta \simeq 0 \leftrightarrow x_a \simeq x_b$

What about $A_{\rm LL}^{\pi}$ measurements away from $\eta \simeq 0$?

idea: $|\eta| \gg 0$: partonic system boosted

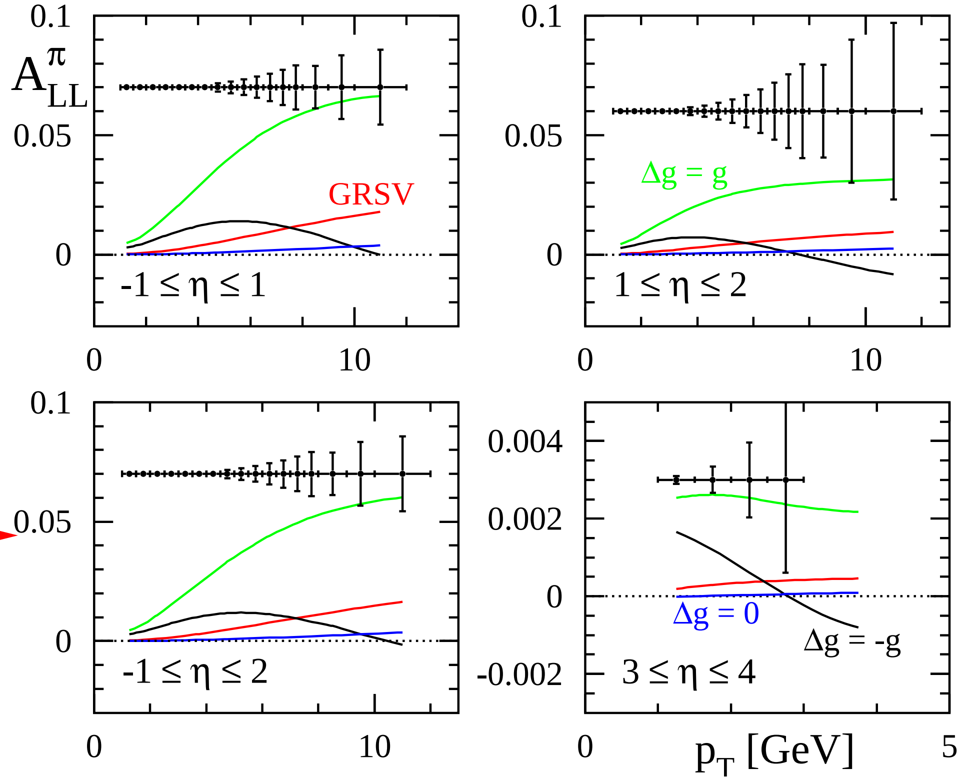
$\longrightarrow$ probes highly asymmetric x_a, x_b

expect: dominance of qg sets in earlier

$\longrightarrow$ sign/size of $A_{\rm LL}^{\pi}$ tied to sign/size of Δg

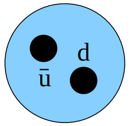
error estimates for $\mathcal{L} = 7\,\mathrm{pb}^{-1}$, $\mathcal{P} = 0.4$

[more plots on Bernd Surrow's homepage]

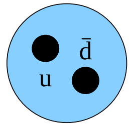


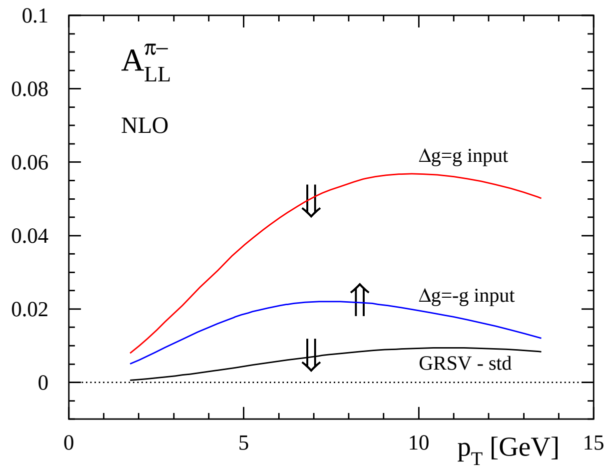
High-$\mathbf{p_T}$ Hadron Production at RHIC (cont.)

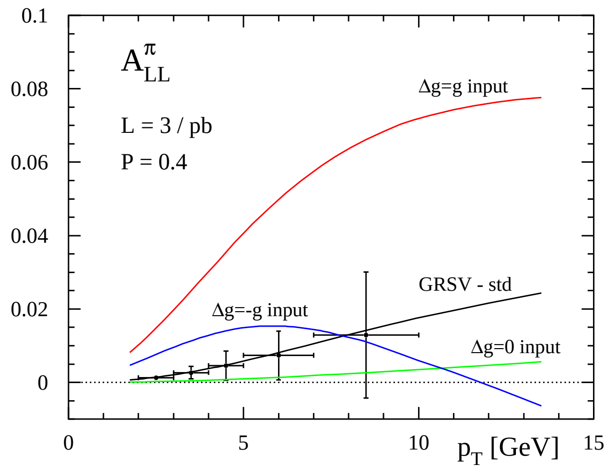
with more luminosity one can go to higher p_T at $\langle\eta\rangle \simeq 0$ *plus* $A_{\rm LL}^{\pi^\pm}$ vs. $A_{\rm LL}^{\pi^0}$

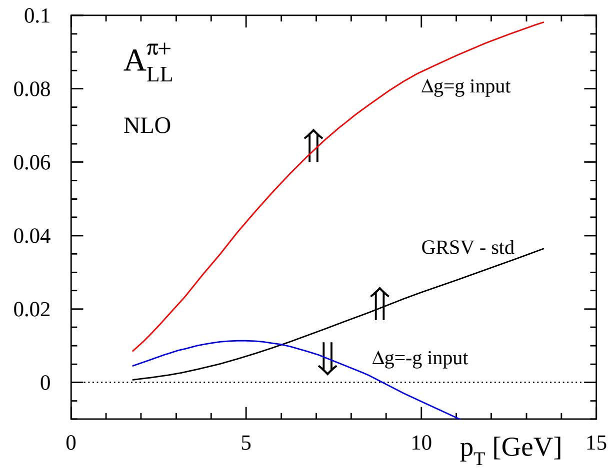
π^- 

π^0

π^+ 





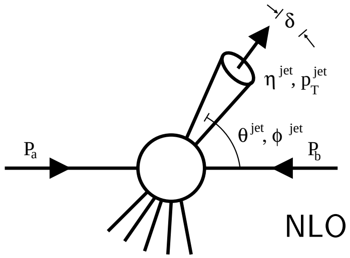


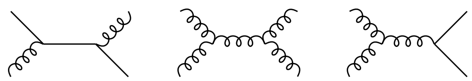
idea: qg starts to dominate for $p_T \gtrsim 5\,\mathrm{GeV}$ and $D_u^{\pi^+} > D_u^{\pi^0} > D_u^{\pi^-}$, $D_g^{\pi^+} = D_g^{\pi^-}$

expect: sensitivity to sign of Δg, e.g., positive Δg: $A_{\rm LL}^{\pi^+} > A_{\rm LL}^{\pi^0} > A_{\rm LL}^{\pi^-}$

High-p_T Jet Production at RHIC

single-incl. jet production:

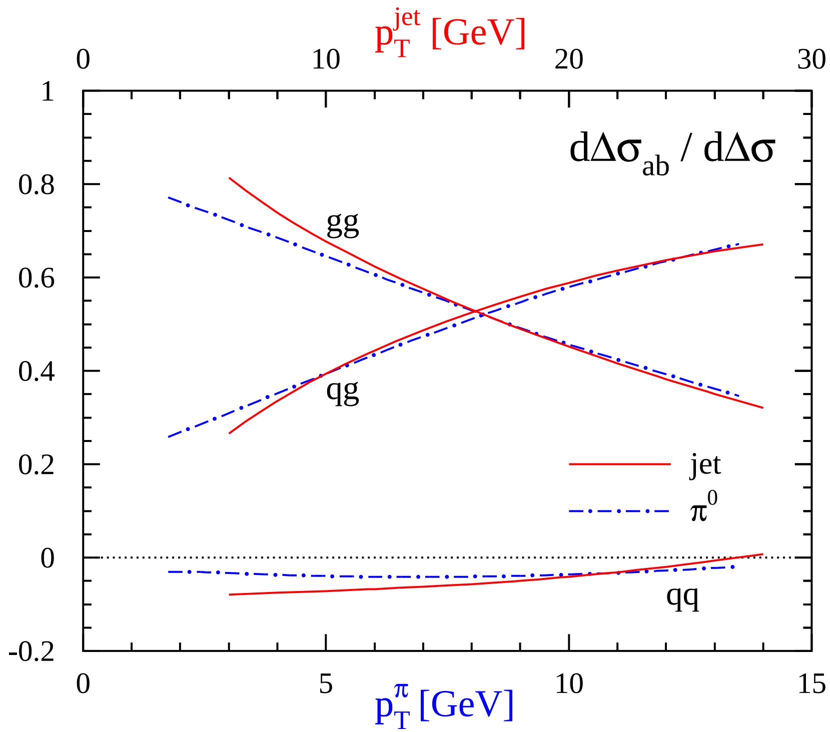




NLO: Jäger, MS, Vogelsang; de Florian, Frixione, Signer, Vogelsang

jet $=$ bunch of particles in a small pencil-like cone; all final-state sing. cancel

jet production proceeds through the same partonic subprocesses as π-production:



π's have roughly $\langle z \rangle \simeq 0.5$:

$\rightarrow$ π with $p_T \simeq$ jet with $2p_T$

comparison to hadrons:

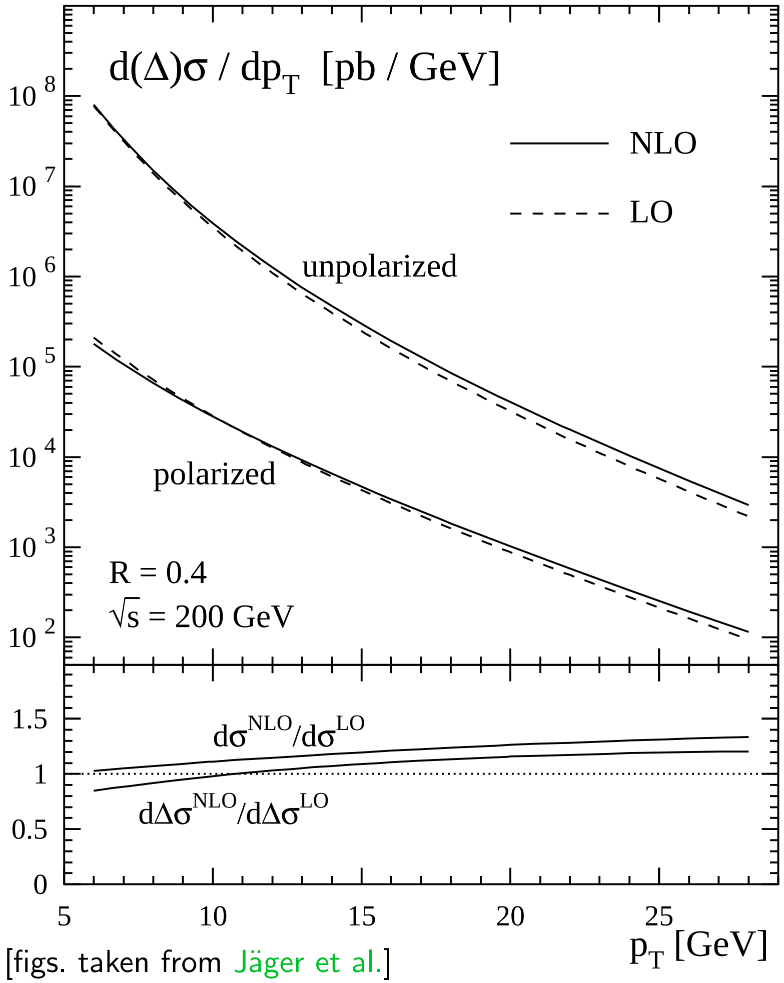
✓ higher rates

✓ no uncertainties from $D(z)$

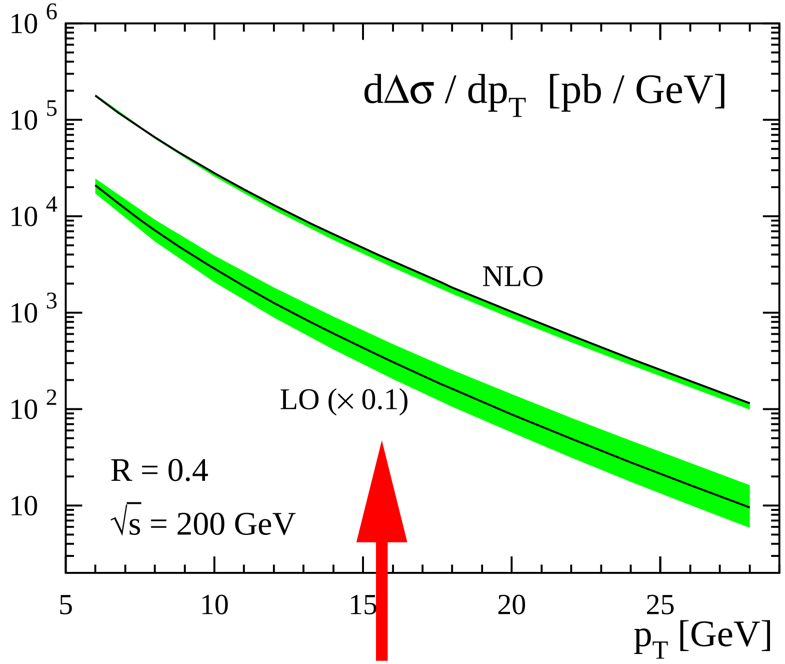
× dependence on precise definition of jet

High-p_T Jet Production at RHIC (cont.)

pQCD results for jet-production at $\sqrt{S} = 200\,\mathrm{GeV}$, $R_{\mathrm{cone}} = 0.4$ (SCA), $|\eta| \leq 1$:



[figs. taken from Jäger et al.]



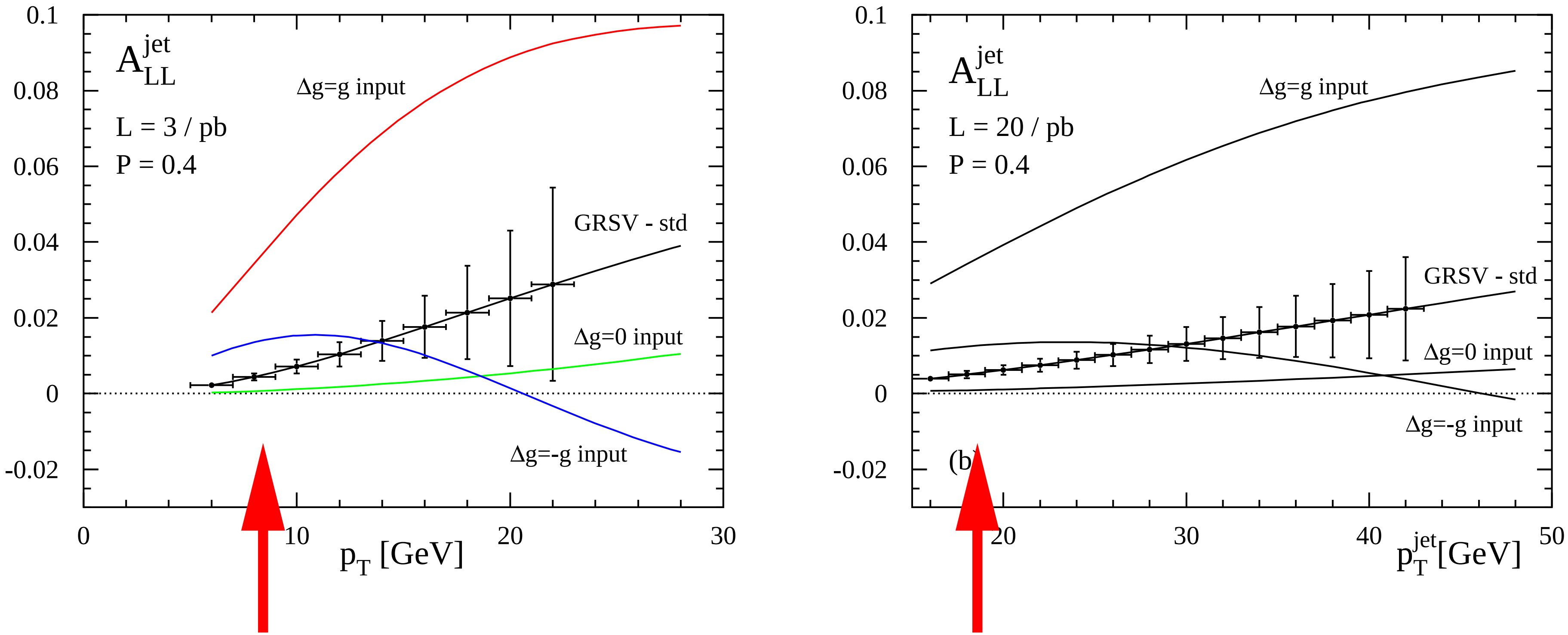
μ_f dependence much reduced in NLO

theoretical uncertainties even smaller than for hadrons

High-$\mathbf{p_T}$ Jet Production at RHIC (cont.)

not surprisingly, $A_{\rm LL}^{\rm jet}$ is sensitive to gluon polarization Δg: [fig. taken from Jäger, MS, Vogelsang]

$\sqrt{S} = 200\,\mathrm{GeV}$, $R_{\rm cone} = 0.4$ (SCA), $0 \leq \eta \leq 1$ $\qquad$ $\sqrt{S} = 500\,\mathrm{GeV}$, $R_{\rm cone} = 0.7$ (SCA), $|\eta| \leq 1$



again: at small p_T no sensitivity to sign of Δg

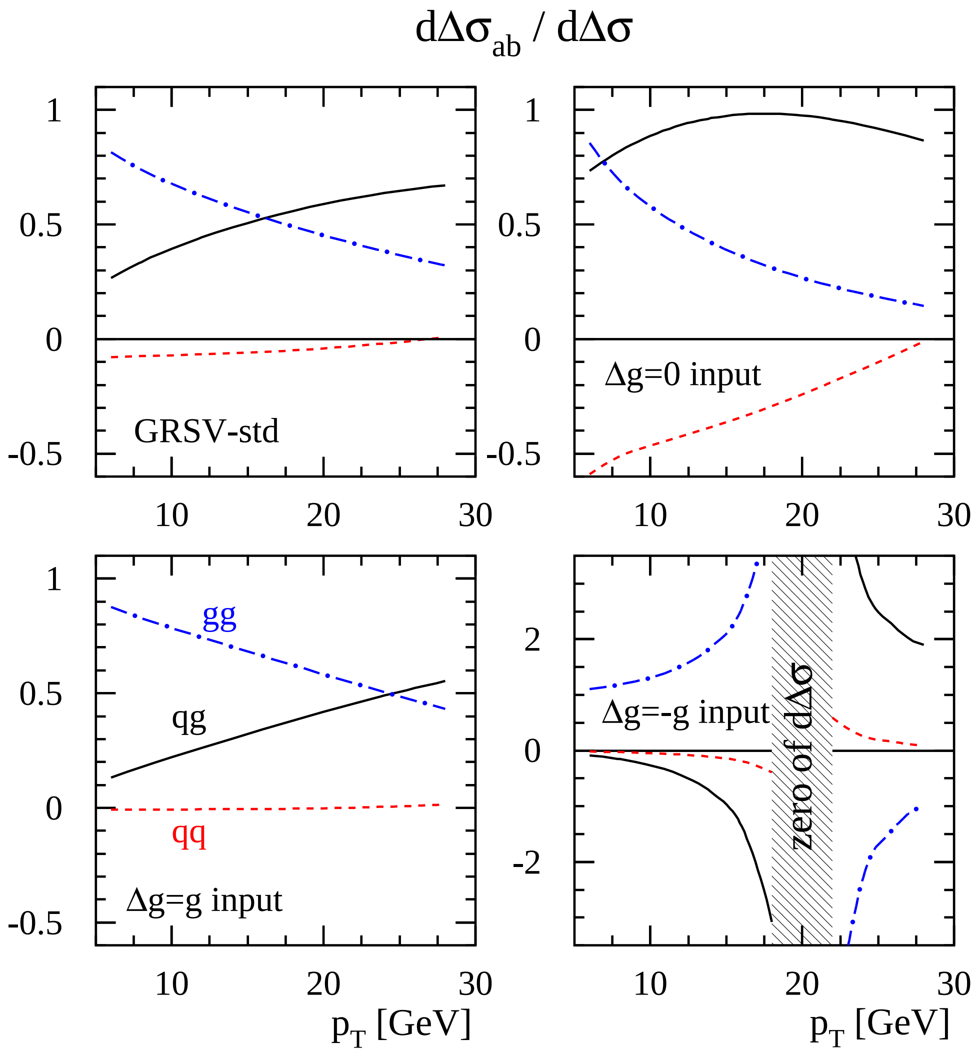
High-p_T Jet Production at RHIC (cont.)

subprocess contributions

for different Δg:

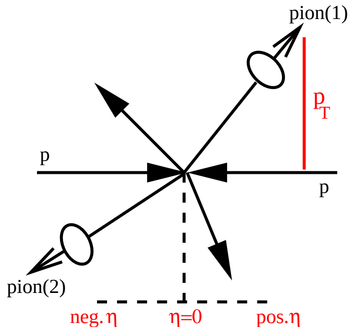
very similar to pion production

(as expected)



Outlook: calculations in the pipeline

- **high-$\mathbf{p_T}$ hadron pairs**



Jäger, Owens, MS, Vogelsang

status: Monte-Carlo code almost ready

feedback: at which observables ($p_{T,1},\ p_{T,2},\ M_{\rm pair}, \ldots$) would you like to look at?

- **$\mathbf{A_{TT}}$ for single inclusive high-$\mathbf{p_T}$ hadrons**

Mukherjee, MS, Vogelsang

status: almost done (have to put everything together and produce a code)

- **heavy flavor pair production**

MS, volunteers

status: some homework to be done (matrix elements known from Bojak, MS)

have to setup a MC code to study exp. relevant observables